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Amendments of Severe Saline-Sodic Paddy Land: Optimal Combination of Phosphogypsum, Farmyard Fertilizer, and Wood Peat

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Abstract: We aimed to determine the optimal combination of amendments to increase rice yields in saline-sodic soil. The effects of different proportions of phosphogypsum (P), farmyard fertilizer (F), and wood peat (W) across the main growth period of rice were studied. A total of 14 treatments were designed based on the "3414" fertilizer effect field experiment scheme, with 3 factors (P, F, and W) and 4 application levels per factor. Application of a combination of P, F, and W reduced soil pH and electrical conductance (EC) ($p < 0.05$), increasing rice yields. The theoretical rice yield after treatment $P_2F_2W_2$ (P 30, F 50, and W 30 t·ha^{-1}) was 5819.20 kg·ha^{-1}, which was 32.52-fold higher than that after $P_0F_0W_0$ (P, F, and W, 0 t·ha^{-1}). Panicle weight, number of total filled grains, total grain weight, and seed-setting rate were 9.76, 17.35, 32.11, and 3.96 times higher than those in the control treatment, respectively. Compared with the control $P_0F_0W_0$ treatment, soil pH in $P_2F_2W_2$ in 0–5, 5–10, 10–15, and 15–20 cm depth decreased by 12.69, 12.32, 11.18, and 10.70%, respectively, and soil EC was 1.06-fold, and 70.79, 49.30, and 47.76% higher, respectively. Overall, we found that the $P_2F_2W_2$ treatment, with a combination of P, 29.09–32.38 t·ha^{-1}; F, 40.36–46.97 t·ha^{-1}; and W, 19.57–23.95 t·ha^{-1} was optimal in this experiment.

Keywords: severe saline-sodic land; amendment; rice; theoretical yield

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1. Introduction

Saline-alkali soils, characterized by high salinity and alkalinity, are widely distributed and found in more than 100 countries globally [1]. Within the context of arable land, this soil type is an important reserve resource that impacts world food security. In China, saline-alkali land covers an area of 0.1 billion hectares (ha), and approximately 37 million hectares of this land are available for use [2]. A portion of this available land is the Northeast saline-sodic land (i.e., 7.65 million hectares), largely concentrated in the Songnen Plain. In terms of physiochemical properties, it is rich in $NaCO_3$ and $NaHCO_3$ [3], which contributes to its highly alkaline state; overall, this stretch of land is not ideal for practicing agriculture [4]. Rice is one of the three major food crops in China, accounting for 27% and 34% of China's planted area and output, respectively [5–8]. At present, several studies have shown that efforts to plant rice in saline-alkali land are an effective measure for improving the use of saline-alkali land resources to ensure food security [9–12]. In terms of measures that have been applied to increase the use of saline-alkali land, amendment application is one of the simplest and most effective methods [13]. Therefore, research delving into the further improvement of this measure is important for increasing the utilization of saline-alkali land. Phosphogypsum (P) is a by-product of the phosphoric acid industry; it mainly consists of calcium phosphate and a small amount of phosphorus. P is available in large quantities across many parts of the world, and more than 22 and 110 million tons of phosphoric acid and P by-products, respectively, are produced annually [14,15]. In terms of production, China is among the largest producers of P, with an annual production of 76 million tons [16]. P is effective at increasing the utilization of saline-alkali land, and the appropriate application amount in severe saline-sodic land is 30 $t \cdot ha^{-1}$ [17–20]. Moreover, the application of farmyard fertilizer (F) can improve a variety of soil physiochemical and biological characteristics [21–25]. Regarding rice production, this strategy can significantly up-regulate a variety of growth-linked genes [26], enhance leakage [27], and thus increase crop yield [28]. Additionally, wood peat (W) can be used to optimize saline-alkali soil for agriculture [29]. By reducing pH, total salt content and alkalinity, and bulk density and soil alkalinity, it can increase organic matter [30,31] and promote the absorption of nutrients by plants, thus increasing yield. It has been shown that 30 $t \cdot ha^{-1}$ is the optimal amount of W that should be added to newly reclaimed land [32]. Numerous studies (theoretical and practical) have been conducted to improve salinization-linked issues in the western Songnen Plain [17,33–35]. However, only a few studies have been conducted to determine the optimal manner to combine and apply (i.e., dosage) P, organic fertilizer, and W in this severely saline-sodic land.

The "3414" experimental design refers to a field experiment recording the effect of the fertilizer on plant growth and has been widely used at home and abroad. The experimental design includes 3 factors (here: P, F, and W) and 4 levels of administration, resulting in 14 treatments. It follows a D-optimal design for quadratic regression and has the advantages of reduced required processing and high efficiency [36–38]. Thus, this method was used in this experiment to comprehensively analyze and evaluate the effects of different dosage ratios on rice yield and its constituent factors, soil pH, and electrical conductivity (EC). We aimed to elucidate the optimal dosage ratio of amendments to improve rice yield and to provide a theoretical basis to optimize the physiochemical properties of saline-sodic land for the cultivation of rice.

2. Materials and Methods

2.1. Study Site

The study was conducted at the National Field Scientific Observation and Research Station of Farmland Ecosystem (45° 36′ N, 123° 53′ E) in Da'an, Jilin, China, in 2022 (Figure 1). The site has a temperate continental monsoon climate, with an average annual air temperature of 4.3 °C. The average air temperature during the growing season is 13.7 °C, whereas the average air temperature during the non-growing season is −4.4 °C. The average annual rainfall is 431.7 mm, with approximately 56% of rainfall concentrated between July and August, and the annual frost-free period is approximately 137 days. The soil of the experimental site is classified as alkaline salt-affected soil. The salt component in the soil consists mainly of soda ($NaHCO_3$ and Na_2CO_3).

Figure 1. Map showing the National Field Scientific Observation and Research Station of Farmland Ecosystem in the Da'an, Jilin, China study site (marked in red), (based on Map data ©2021 Microsoft CorporationGS [2021]1731, ©2021TomTom).

2.2. Test Materials and Design

2.2.1. Test Materials

The soil tested in this experiment was classified as severe saline-sodic, with the following characteristics: pH 10.1, EC 981.5 μS·cm^{-1}, soluble Ca 1720 mg·kg^{-1}, soluble Na 2450 mg·kg^{-1}, and exchangeable sodium saturation percentage (ESP) 48%. According to the classification by the World Soil Resources Reference Bank (WRB), the soil at the test site is classified as "Solonetz". The rice cultivar of interest was "Dongdao 122", independently cultivated by the Northeast Institute of Geography and Agroecology, Chinese Academy of Sciences. Table 1 shows the physicochemical properties of P, F, and W tested. W was provided by the Institute of Soil Science, Chinese Academy of Sciences.

Table 1. Test report of P, F, and W.

Detection Index	Test Result		
	P	**F**	**W**
pH	4.5	7.6	5.41
Cd (%)	0.0001	<0.1	0.13
Cr (%)	0.0005	15.4	3.68
As (%)	0.0003	6.9	1.19
Pb (%)	0.0012	7.3	3.67
Hg (%)	0.0001	0.2	0.04
$^{a}(H_2O)$ (%)	16	28.4	
S (%)	18.4		
N (%)		2.31	0.685
Organic matter (%)		35.3	90.98
P_2O_5 (%)		1.63	0.007
K_2O (%)		1.94	0.015
Number of fecal coliforms (n·g^{-1})		<3.0	
Mortality of ascarid egg (%)		100	

Table 1. *Cont.*

Detection Index	Test Result		
	P	F	W
GI (%)		80.2	
Weed seed activity (%)		0.0	
Mechanical impurities (%)		0.0	
Cl^- (%)		0.75	
Dry bulk density ($g{\cdot}cm^{-4}$)			0.412
Total amount of humic acid (%)			45.35
$CaSO_4{\cdot}2H_2O$ (%)	90		

a(H_2O) represents the mass fraction of free water.

2.2.2. Experimental Design

We designed a pot experiment and adopted the "3414" experimental scheme, which entailed arranging elements in random blocks. Application of the three factors (P, F, and W) was set at four levels (0–3) as follows: no application at level 0; regular application at level 2; and 50% and 150% (i.e., excess application) of level 2 rates at levels 1 and 3, respectively. A total of 14 treatments (Table 2) were randomly arranged, with each treatment repeated five times. Overall, we used 70 pots; a hole was punctured in each pot, and five plants were grown in each hole. The rice was transplanted on May 22, and field management was conducted in accordance with local conventional methods during the whole growth period.

Table 2. Proportion treatment and the amount of P, F, and W.

Numbering	Treatment	Code			Application Rate ($t{\cdot}ha^{-1}$)		
		P	F	W	P	F	W
1	$P_0F_0W_0$	0	0	0	0	0	0
2	$P_0F_2W_2$	0	0.67	0.67	0	50	30
3	$P_1F_2W_2$	0.33	0.67	0.67	15	50	30
4	$P_2F_0W_2$	0.67	0	0.67	30	0	30
5	$P_2F_1W_2$	0.67	0.33	0.67	30	25	30
6	$P_2F_2W_2$	0.67	0.67	0.67	30	50	30
7	$P_2F_3W_2$	0.67	1	0.67	30	75	30
8	$P_2F_2W_0$	0.67	0.67	0	30	50	0
9	$P_2F_2W_1$	0.67	0.67	0.33	30	50	15
10	$P_2F_2W_3$	0.67	0.67	1	30	50	45
11	$P_3F_2W_2$	1	0.67	0.67	45	50	30
12	$P_2F_1W_1$	0.67	0.33	0.33	30	25	15
13	$P_1F_2W_1$	0.33	0.67	0.33	15	50	15
14	$P_1F_1W_2$	0.33	0.33	0.67	15	25	30

The numbers in the bottom corner of the second column are the level codes of each factor. P, phosphogypsum; F, farmyard fertilizer; W, wood peat.

2.3. Determination Index and Method

2.3.1. Agronomic Characteristics of the Main Growth Period

Throughout the rice growth period, the plant height, tiller, and chlorophyll relative content (soil plant analysis development (SPAD)) were evaluated. For SPAD measurements, the most representative plant in each hole was used for SPAD-1 and SPAD-2 measurements by inverting one leaf in each hole. The SPAD values were measured using a SPAD-502 chlorophyll analyzer (Soil-Plant Analyses Development, Minolta Camera Co., Ltd., Osaka, Japan) [39]. Measurements were obtained on 22 July, 1 August, 11 August, 21 August, 1 September, and 11 September. The number of crown roots was calculated as follows:

Number of crown roots = 162.426 + 20.43 × number of crown tillers [40].

2.3.2. Theoretical Yield and Its Components

The rice was harvested on 25 September, and yield components were then determined, allowing for the calculation of theoretical yield, which was performed as follows:

Theoretical yield = Effective panicle per unit area × Number of grains per ear × Seed setting rate × 1000-grain weight × 100.

2.3.3. Soil pH and EC

Soil samples from 0–5, 5–10, 10–15, and 15–20 cm soil depths were collected from the beginning of transplanting on 22 May to the end of yield measurement on 25 September. There were 14 experimental treatments in total, each with 5 replicates. After harvest, soil samples at depths of 0–5, 5–10, 10–15, and 15–20 cm were extracted from each pot, air-dried, and filtered through a 2-mm sieve, mixed with water at a ratio of 1:5, stirred for 30 min, and settled for at least 2 h. A PHS-3C digital pH meter (Shanghai Leici, Shanghai, China) and a DDS-307 EC meter (Shanghai Leici, Shanghai, China) were used to determine pH and EC, respectively.

2.4. Data Processing

SPSS 19.0 statistical software and Excel 2019 were used to collate and analyze the raw data. Origin 2021 was then used to plot the resultant output. $p < 0.05$ was considered to indicate significance.

3. Results

3.1. Effects of Amendments on Agronomic Characteristics during the Main Growth Period of Rice

As shown in Figure 2, SPAD values, plant height, tillering, and the number of crown roots in rice at the main growth stages were significantly superior after applying amendments than those in the control treatment ($P_0F_0W_0$).

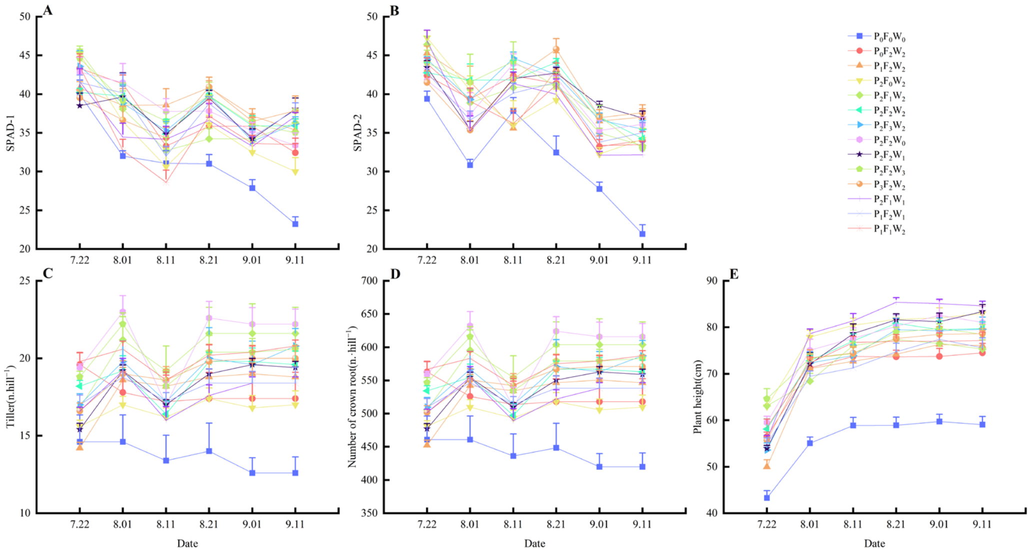

Figure 2. Effects of amendment application on SPAD-1 (**A**), SPAD-2 (**B**), plant height (**C**), tiller (**D**), and number of crown roots (**E**).

Plant height, tiller, SPAD-1 and SPAD-2 values, and number of crown roots at the mature stage were significantly improved after the application of amendments compared to those in the control treatment, and there were significant differences between treatments ($p < 0.05$) (Table 3).

Table 3. Effects of amendment application on agronomic characteristics of rice at maturity.

Treatment	Plant Height (cm)	Tiller (n.·hill^{-1})	SP AD-1	SP AD-2	Number of Crown Root (n.·hill^{-1})
$P_0F_0W_0$	59.08 ± 1.75 ^{e}	12.60 ± 1.03 ^{e}	23.22 ± 0.94 ^{e}	21.94 ± 1.20 ^{d}	419.84 ± 21.03 ^{e}
$P_0F_2W_2$	74.50 ± 2.04 ^{d}	17.40 ± 1.69 ^{cd}	32.44 ± 1.18 ^{cd}	34.02 ± 1.15 ^{abc}	517.91 ± 34.55 ^{cd}
$P_1F_2W_2$	76.08 ± 3.65 ^{cd}	18.80 ± 1.07 ^{abcd}	35.38 ± 1.44 ^{abc}	37.02 ± 1.10 ^{ab}	546.51 ± 21.81 ^{abcd}
$P_2F_0W_2$	82.98 ± 1.59 ^{abc}	17.00 ± 0.89 ^{d}	30.02 ± 1.78 ^{d}	34.16 ± 1.44 ^{abc}	509.74 ± 18.27 ^{d}
$P_2F_1W_2$	75.32 ± 2.01 ^{d}	21.60 ± 1.69 ^{ab}	36.30 ± 1.75 ^{abc}	33.34 ± 2.17 ^{bc}	603.71 ± 34.55 ^{ab}
$P_2F_2W_2$	79.72 ± 1.45 ^{abcd}	19.60 ± 0.87 ^{abcd}	35.90 ± 0.91 ^{abc}	34.26 ± 1.17 ^{abc}	562.85 ± 17.81 ^{abcd}
$P_2F_3W_2$	79.60 ± 2.61 ^{abcd}	20.80 ± 1.11 ^{abc}	36.18 ± 0.91 ^{abc}	35.48 ± 1.13 ^{abc}	587.37 ± 22.75 ^{abc}
$P_2F_2W_0$	81.08 ± 3.45 ^{abcd}	22.20 ± 0.97 ^{a}	33.38 ± 1.62 ^{bcd}	36.12 ± 0.87 ^{abc}	615.97 ± 19.81 ^{a}
$P_2F_2W_1$	83.38 ± 1.53 ^{ab}	19.40 ± 0.40 ^{abcd}	38.08 ± 1.44 ^{a}	36.90 ± 0.92 ^{ab}	558.77 ± 8.17 ^{abcd}
$P_2F_2W_3$	78.50 ± 2.10 ^{abcd}	20.60 ± 0.98 ^{abc}	35.04 ± 1.21 ^{abc}	32.98 ± 0.39 ^{bc}	583.28 ± 20.02 ^{abc}
$P_3F_2W_2$	78.62 ± 0.75 ^{abcd}	20.00 ± 0.84 ^{abcd}	37.84 ± 1.92 ^{a}	37.60 ± 1.01 ^{a}	571.03 ± 17.09 ^{abcd}
$P_2F_1W_1$	84.64 ± 0.97 ^{a}	18.40 ± 0.40 ^{bcd}	37.14 ± 0.49 ^{ab}	32.18 ± 1.71 ^{c}	538.34 ± 8.17 ^{bcd}
$P_1F_2W_1$	75.58 ± 2.15 ^{d}	18.40 ± 1.03 ^{bcd}	37.94 ± 0.93 ^{a}	35.02 ± 1.32 ^{abc}	538.34 ± 21.03 ^{bcd}
$P_1F_1W_2$	77.16 ± 1.83 ^{bcd}	20.80 ± 0.37 ^{abc}	33.48 ± 0.84 ^{bcd}	33.50 ± 0.40 ^{bc}	587.37 ± 7.64 ^{abc}

Different letters indicate significant differences between treatments ($p < 0.05$).

3.2. Effects of Amendments on the Theoretical Yield and Yield Components of Rice

3.2.1. Yield Components

Application of various combinations of P, F, and W affected yield components. Panicle weight after each treatment was significantly higher than that in the control ($p < 0.05$), with the weight in $P_2F_2W_2$ showing the highest value (22.65 g); specifically, panicle weight was 45.40, 41.37, and 10.23% and 9.76 times higher than that in the treatments without P, F, or W and in the control treatment, respectively. Panicle weight in $P_2F_2W_2$ was significantly different from that in the $P_0F_0W_0$, $P_0F_2W_2$, $P_1F_2W_2$, $P_2F_0W_2$, and $P_1F_1W_2$ treatments ($p < 0.05$). The number of total filled grains was significantly higher than that in the control ($p < 0.05$) and was the highest (1009.00) in the $P_2F_2W_2$ treatment; it was 50.15, 71.37, 15.84, and 17.35% higher than that in treatments without P, F, or W and in the control treatment, respectively. Additionally, it was significantly different from treatments $P_0F_0W_0$, $P_0F_2W_2$, $P_2F_0W_2$, and $P_1F_1W_2$ ($p < 0.05$). The total grain weight was significantly higher than that in the control ($p < 0.05$), and $P_2F_2W_2$ resulted in the highest (19.67 g) total grain weight, which was 58.31, 66.26, 18.25, and 32.11% higher than that in the treatments without P, F, or W and the control, respectively. Furthermore, total grain weight was significantly different from treatments $P_0F_0W_0$, $P_0F_2W_2$, and $P_2F_0W_2$ ($p < 0.05$). The seed setting rate was significantly higher than that in the control ($p < 0.05$), and $P_2F_2W_2$ produced the highest (73.70%) seed setting rate, and it was 16.56, 30.37, 26.18, and 3.96% higher than that for no application of P, F, or W and in the control. It was significantly different from treatments $P_0F_0W_0$, $P_2F_2W_0$, and $P_2F_0W_2$ ($p < 0.05$) (Figure 3).

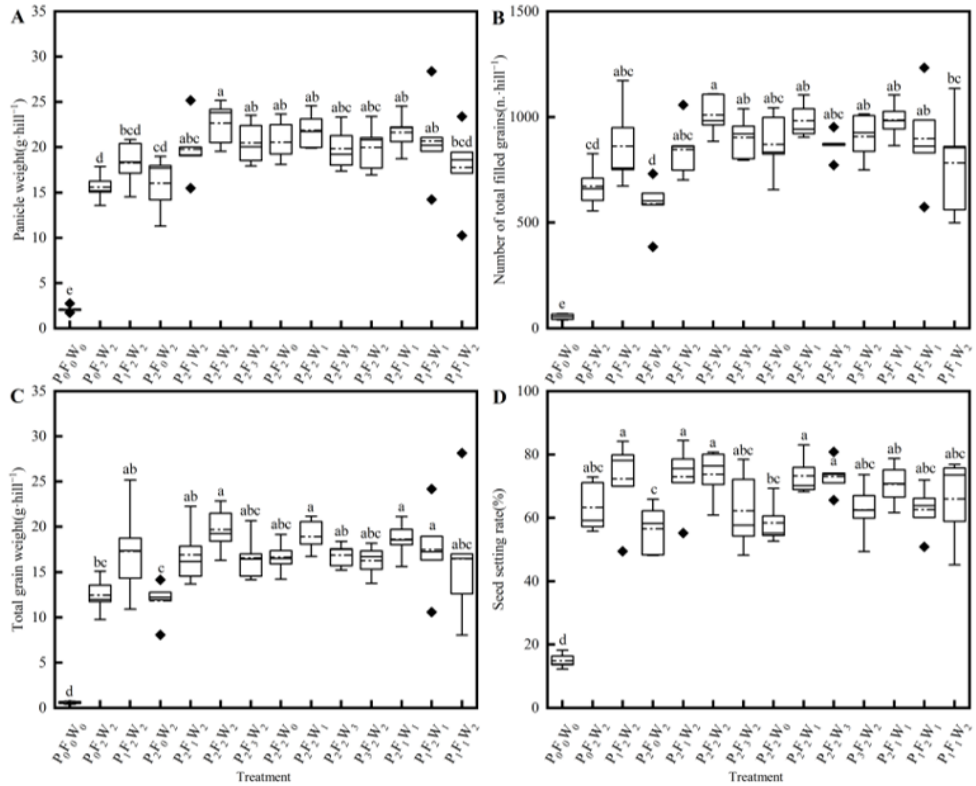

Figure 3. Effects of amendment application on panicle weight (**A**), number of total filled grains (**B**), total grain weight (**C**), and seed setting rate (**D**). Results were tested by Duncan's multiple range test. Different letters indicate significant differences among the treatments ($p < 0.05$).

3.2.2. Effect of Amendments on Rice Theoretical Yield

The theoretical yield after each treatment and application of the amendment was significantly higher than that of the control ($p < 0.05$), and the $P_2F_2W_2$ treatment resulted in the highest theoretical yield (5819.20 kg·ha^{-1}). The $P_2F_2W_2$ treatment increased yield by 62.76, 73.02, 19.05, and 32.52% compared with the treatments without P, F, or W and the control, respectively. The yield after the $P_2F_2W_2$ treatment was significantly different from that after treatments $P_0F_0W_0$, $P_0F_2W_2$, $P_2F_0W_2$, and $P_1F_1W_2$ ($p < 0.05$) (Figure 4).

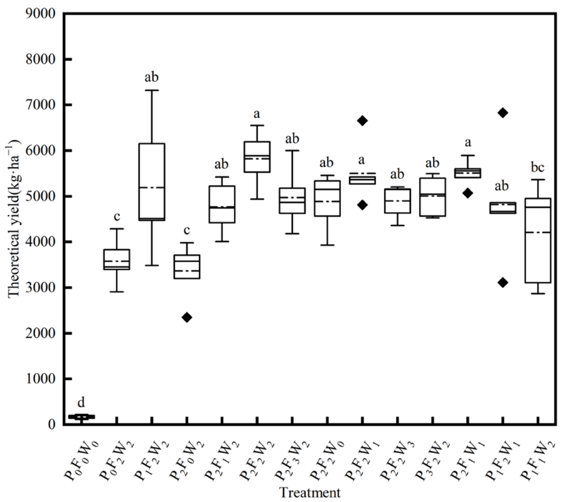

Figure 4. Effect of amendment application on theoretical yield. Results were tested by Duncan's multiple range test. Different letters indicate significant differences among the treatments ($p < 0.05$).

3.3. Application Effect and Optimum Dosage of the Amendment

3.3.1. Amendment Standardization

Data standardization was adopted to standardize the application of P, F, and W. Thus, the observed value of a variable was subtracted from the minimum value and then divided by the value range for that variable. That is, Xik = [xik − min (xk)] × Rk^{-1}. After standardization, the observed values of various variables range between 0 and 1, and the standardized data are pure quantities without units. The standardized results are presented in Table 2.

3.3.2. Effect of Single Improvement Factor on Rice Yield

The yields were compared when any two of factors P, F, and W were set to level 2; that is, between treatments 2, 3, 6, and 11; 4, 5, 6, and 7; and 8, 9, 6, and 10. The relationship between the application amount of P, F, or W and yield was visualized using a scatter plot (Figure 5).

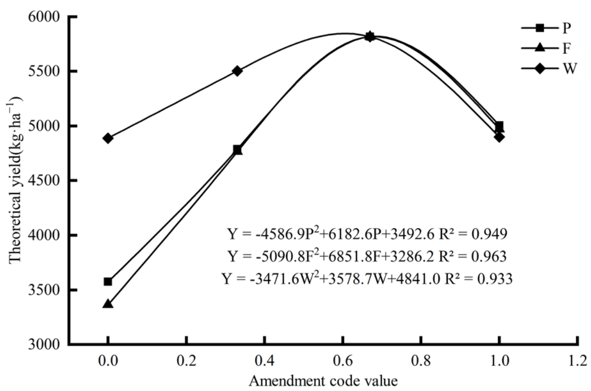

Figure 5. Single factor effect of P (■), F (▲), and W (◆) on yield.

With the amount of P, F, or W as the independent variable and rice yield as the dependent variable, regression analysis was performed to fit the one-element quadratic regression model. The obtained formulas are presented in Table 4, Equations (1)–(3).

Table 4. Fitting results of single factor equation.

Treatments	Quadratic Equation with One Unknown	Significant Test			NO.
		R^2	F	$F_{0.05}$	
P	$Y = -4586.9\ P^2 + 6182.6\ P + 3492.6$	0.949	9.3	0.226	(1)
F	$Y = -5090.8\ F^2 + 6851.8\ F + 3286.2$	0.963	13.0	0.193	(2)
W	$Y = -3471.6\ W^2 + 3578.7\ W + 4841.0$	0.933	6.9	0.260	(3)

In the formula, Y represents rice yield under different treatments of P, F, and W; the application amount of phosphogypsum, farmyard fertilizer, and wood peat, respectively.

Through the significance test analysis and estimates for R^2 and F values, the results showed that the unitary quadratic regression model fits well with the data, indicating that it truly reflects the regression relationship between P, F, and W and yield. The quadratic equations for each variable are open downward parabolas (Figure 5); that is, with the increase of the application amount of P, F, or W, the output initially increases and then decreases. The primary term is positive, while the secondary term is negative, indicating the presence of a maximum value in the equation. By solving Equations (1)–(3), the maximum output values and the optimal amount of P, F, and W, respectively, can be obtained (Table 5).

Table 5. Optimal single-factor application amount and corresponding yield.

Treatments	Optimal Application Amount ($t \cdot ha^{-1}$)	Corresponding Yield ($kg \cdot ha^{-1}$)
P	30.33	5575.92
F	50.47	5591.69
W	23.19	5763.22

According to the results of the single factor effect, the optimal coding values of P, F, and W were 0.67, 0.67, and 0.52, respectively, corresponding to 30.33, 50.47, and 23.19 $t \cdot ha^{-1}$, respectively; the corresponding yields were 5575.92, 5591.69, and 5763.22 $kg \cdot ha^{-1}$, respectively. It is apparent that the optimal application amount of P is approximately that of level 2, while those of organic F and W are approximately those of levels 2 and 1–2, respectively. During testing, when the dosage of P, F, and W was 30, 50, and 30 $t \cdot ha^{-1}$, respectively, the maximum yield was 5819.136 $kg \cdot ha^{-1}$, which theoretically reflects increases by 62.76, 73.01, and 19.05% compared with those without P, F, or W, respectively. Based on the above analysis, the highest rice yield was obtained when the single-factor application level was 2.

3.3.3. Effect of Two Factors on Rice Yield

An interaction effect between P, F, and W can be observed. When W was supplied at level 2 (Figure 6A), and P increased from level 1 to 2, application of F at level 1 led to a yield increase by 555.43 $kg \cdot ha^{-1}$, while, at level 2, yield increased by 1029.12 $kg \cdot ha^{-1}$. This shows that F at level 2 influences the effect of P, and P at level 2 increases from level 1 to level 2. Applying W at level 1 increased yield by 687.37 $kg \cdot ha^{-1}$ and, at level 2, by 1029.12 $kg \cdot ha^{-1}$, indicating that W influences the effect of P at level 2. When W was at level 2 (Figure 6B), for F increases from level 1 to 2, yield increased by 580.06 $kg \cdot ha^{-1}$ at level 1 and by 1053.75 $kg \cdot ha^{-1}$ at level 2, indicating that P was conducive to the effectiveness of F fertilizer effect at level 2. When P was applied at level 2, and F increased from level 1 to level 2, the yield was reduced by 0.84 $kg \cdot ha^{-1}$ for the application of W at level 1; however, it increased by 1053.75 $kg \cdot ha^{-1}$ when W was applied at level 2, indicating that W was beneficial to the effectiveness of the application of F at level 2. When F was at level 2 (Figure 6C), and W increased from level 1 to 2, the yield when P was applied at level 1 decreased by 27.67 $kg \cdot ha^{-1}$, while, at level 2, the yield increased by 314.08 $kg \cdot ha^{-1}$, indicating that P is conducive to the W effect at level 2. When P was at level 2, and W increased from level 1 to 2, the yield was reduced by 740.51 $kg \cdot ha^{-1}$ when F was supplied at level 1, while it increased by 314.08 $kg \cdot ha^{-1}$ for F application at level 2, indicating that F is conducive to the development of the effect of W at level 2.

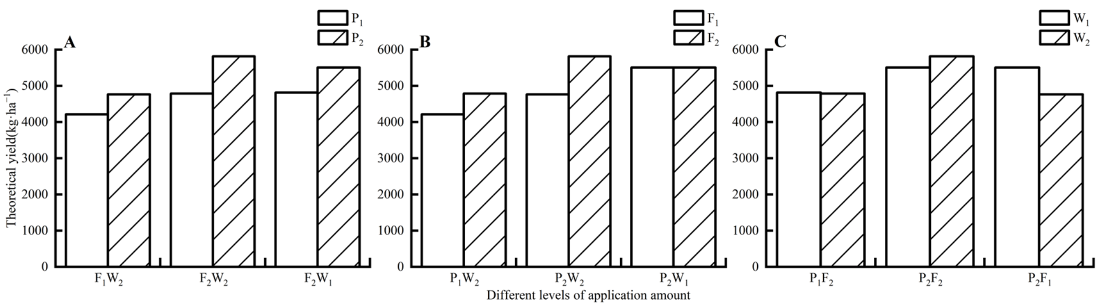

Figure 6. Interactive effects of PF (**A**), PW (**B**), and FW (**C**) on yield.

One factor in the test scheme was fixed at level 2; that is, the yield of P, F, and W application conditions were analyzed according to the results of test treatments 2, 3, 4, 5, 6, 7, 11, and 14; 2, 3, 6, 8, 9, 10, 11, and 13; and 4, 5, 6, 7, 8, 9, 10, and 12. Through regression analysis of the interactions P × F, P × W, and F × W, the binary quadratic regression Equations (1)–(3) (Table 6) was obtained. After the regression equation significance test, where Equation (1) $F = 10.277 > F\ 0.05 = 0.091$ and $R^2 = 0.963$; Equation (2)

F = 8.504 > F 0.05 = 0.109 and R^2 = 0.955; and Equation (3) F = 12.775 > F 0.05 = 0.074 and R^2 = 0.970, indicating that there was a significant correlation between the application amount of PF, PW, FW, and the yield. The equation fit was good and in line with the law of decreasing fertilizer returns (i.e., the quadratic term was negative, while the primary term was positive), that is, the typical fertilizer function. The differential partial derivative method was adopted to obtain the highest yield and the best application amount (Table 7).

Table 6. Fitting results of bivariate quadratic model.

Treatment	Binary Quadratic Equations	Significant Test			NO.
		R^2	F	$F_{0.05}$	
P, F	$Y = 648.9 + 6825.0\,P + 7420.8\,F - 4251.6\,P^2 - 4690.8\,F^2 - 1526.5\,PF$	0.963	10.3	0.091	(1)
P, W	$Y = 2096.3 + 7164.8\,P + 4075.3\,W - 4502.5\,P^2 - 2959.3\,W^2 - 1608.8\,PW$	0.955	8.5	0.109	(2)
F, W	$Y = 4730.1 + 3553.4\,F - 132.0\,W - 4986.4\,F^2 - 3004.0\,W^2 + 4746.3\,FW$	0.970	12.8	0.074	(3)

Table 7. Optimal application amount and corresponding yield of two factors.

Treatments	Highest-Yield Application Amount (t·ha^{-1})			Highest Yield (kg·ha^{-1})
	P	F	W	
P, F	30.62	51.02		5495.18
P, W	31.81		22.34	5640.31
F, W		41.56	18.71	5687.37

According to yield analysis, 41.56 t·ha^{-1} of F combined with 18.71 t·ha^{-1} of W generated the highest theoretical yield of 5687.37 kg·ha^{-1}. This was followed by applying 31.81 t·ha^{-1} of P combined with 22.34 t·ha^{-1} of W, resulting in a theoretical yield of 5640.31 kg·ha^{-1}. Applying 30.62 t·ha^{-1} of P combined with 51.02 t·ha^{-1} of F produced the lowest theoretical yield of 5495.18 kg·ha^{-1}.

3.3.4. Three-Factor Improvement Effect Model and Optimal Dosage of Amendments

Based on the "3414" experimental design, with the application amount of P, F, and W as the independent variable and rice yield as the dependent variable, a three-way quadratic regression model was established (Table 8). The significance test showed R^2 = 0.992, F = 57.855, and p <0.01; the fit was good and reached an extremely significant level, in which the quadratic term coefficient was negative, and the primary term coefficient was positive. This was in line with the law of decreasing fertilizer returns and could better reflect the relationship between yield and amendment dosage. Since the mathematical model was obtained after non-dimensional treatment and linear substitution, the absolute value of partial regression coefficients of each primary term can directly reflect the degree of influence of P, F, and W on the yield, which is shown as P>F>W. Meanwhile, the partial regression coefficient was positive, indicating that P, F, and W have a positive effect on the yield and growth of rice.

Table 8. Fitting results of ternary quadratic model.

Ternary Quadratic Equation	Significant Test		
	R^2	F	P
$Y = 189.4 + 9435.7\,P + 5734.1\,F + 1882.3\,W - 4533.5\,P^2 - 4972.7\,F^2 - 2990.3\,W^2 - 2645.7\,PF - 2397.3\,PW + 4016.8\,FW$	0.992	57.9	0.0007

Based on published methods [36–38], seven coding levels between P, F, and W and 152 sets of combination schemes exceeding the mean yield of 4449.00 kg·ha^{-1} were obtained, accounting for 44.32% of the total schemes. Frequency analysis was then used to calculate the frequency of each level of P, F, and W, and a management scheme with a yield greater than the mean yield was obtained (Table 9). The optimal application combinations with 95%

confidence intervals were as follows: P = 0.647–0.720; F = 0.538–0.626; and W = 0.435–0.532. The corresponding optimal application dosage is P, 29.09–32.38 $t \cdot ha^{-1}$; F, 40.36–46.97 $t \cdot ha^{-1}$; and W, 19.57–23.95 $t \cdot ha^{-1}$. When the optimal application mean values for P (30.74 $t \cdot ha^{-1}$), F (43.67 $t \cdot ha^{-1}$), and W (21.76 $t \cdot ha^{-1}$) were substituted into the equation, the optimal application yield was 5670.00 $kg \cdot ha^{-1}$. The yield of 5543.90 $kg \cdot ha^{-1}$ was the closest to that of $P_2F_2W_2$ (i.e., P 30, F 50, and W 30 $t \cdot ha^{-1}$). Therefore, the $P_2F_2W_2$ treatment was the best combination treatment in this experiment.

Table 9. Frequency distribution and application scheme of P, F, and W coding values with higher than average yield.

Item	Code	P		F		W	
		Counts	Frequency (%)	Counts	Frequency (%)	Counts	Frequency (%)
	0	0	0	7	4.6	18	11.8
	0.167	4	2.6	14	9.2	22	14.5
	0.333	18	11.8	22	14.5	26	17.1
	0.5	30	19.7	29	19.1	26	17.1
	0.667	36	23.7	32	21.1	24	15.8
	0.833	35	23	30	19.7	23	15.1
	1	29	19.1	18	11.8	13	8.6
Code the weighted mean		0.683		0.582		0.484	
Standard error		0.019		0.022		0.025	
95% confidence interval		0.647–0.720		0.538–0.626		0.435–0.532	
Optimal fertilizer ($t \cdot ha^{-1}$)		29.09–32.38		40.36–46.97		19.57–23.95	

3.4. Effects of Different Amendments on pH and EC in Topsoil

As shown in Figure 7, the pH in all samples after the application of the amendments was significantly lower than that in the control ($p < 0.05$), and EC increased in most samples compared with that in the control. The soil pH after the $P_2F_2W_2$ treatment in 0–5, 5–10, 10–15, and 15–20 cm layers was 8.86, 8.92, 8.99, and 9.01, respectively, which was 12.69, 12.32, 11.18, and 10.70% lower than that in the control treatment $P_0F_0W_0$. The soil EC values of 959.20, 814.00, 828.00, and 818.60 $\mu S \cdot cm^{-1}$ were 1.06 times and 70.79, 49.30, and 47.76% higher than those in $P_0F_0W_0$, respectively. The pH in the $P_2F_2W_2$ treatment in the top (0–5 cm) soil layer was significantly higher than that in $P_0F_0W_0$-, $P_2F_2W_1$-, $P_1F_2W_2$-, $P_1F_1W_2$-, $P_0F_2W_2$-, and $P_1F_2W_1$-treated soil. The EC in $P_2F_2W_2$-treated soil was significantly higher than that in $P_0F_0W_0$, $P_2F_2W_0$, $P_1F_2W_2$, $P_1F_1W_2$, $P_0F_2W_2$, and $P_1F_2W_1$. The pH in the 5–10 cm layer in $P_2F_2W_2$-treated soil was significantly higher than that in soil treated with $P_0F_0W_0$, $P_2F_2W_1$, $P_2F_1W_2$, $P_1F_2W_2$, $P_0F_2W_2$, $P_1F_1W_2$, and $P_1F_2W_1$. The EC was significantly higher than that in $P_0F_0W_0$-, $P_1F_2W_2$-, $P_1F_1W_2$-, and $P_0F_2W_2$-treated soil layer. In the 10–15 cm soil layer, the pH in the $P_2F_2W_2$ condition was significantly higher than that in treatments $P_0F_0W_0$, $P_3F_2W_2$, $P_1F_1W_2$, $P_1F_2W_2$, $P_1F_2W_2$, and $P_0F_2W_2$; EC was significantly higher than that in soil treated with $P_0F_0W_0$, $P_1F_2W_2$, $P_1F_2W_1$, $P_1F_1W_2$, and $P_0F_2W_2$. Lastly, in the 15–20 cm soil layer, the pH in $P_2F_2W_2$ was significantly higher than that in $P_0F_0W_0$, $P_1F_1W_2$, $P_1F_2W_2$, $P_1F_2W_1$, and $P_0F_2W_2$, and EC was significantly lower than that in $P_2F_3W_2$ and significantly higher than that in $P_0F_0W_0$-, $P_1F_2W_2$-, $P_1F_2W_1$-, and $P_0F_2W_2$-treated soil ($p < 0.05$).

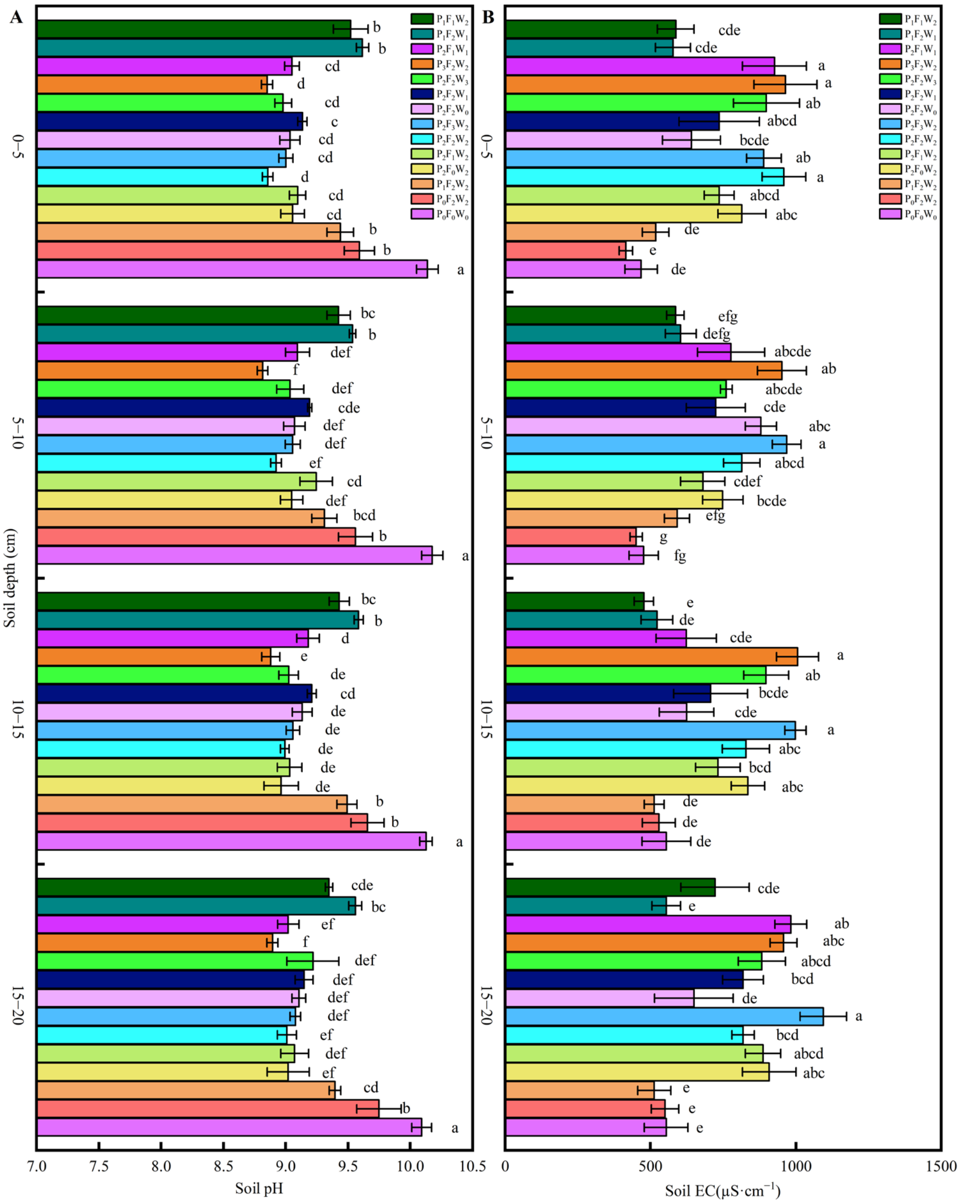

Figure 7. Effects of amendment application on pH (**A**) and EC (**B**) in soil layers 0–5, 5–10, 10–15, and 15–20 cm. Results were tested by Duncan's multiple range test. Different letters indicate significant differences among the treatments ($p < 0.05$).

4. Discussion

The patterns that characterize rice growth in saline-alkali soil impact the yield; specifically, saline-alkaline stress reduces plant height and tillering [41–45]. The results of this study show that the combined application of P, F, and W significantly facilitated the optimal development of rice across its growth period.

A rice panicle is a reservoir of organic matter, which embodies the final economic yield [46]. The resultant yield mainly depends on grain growth and development [47]. Salt stress can reduce rice production by directly affecting panicle development [48,49]. Under increasing salt stress, yield, effective panicle number, number of total filled grains, 1000-grain weight, and seed setting rate decrease significantly [50]. Studies show that applying P can significantly increase rice yield, panicle weight, number of total filled grains, total grain weight, and seed setting rate [17,51]. Additionally, applying F in saline-alkali soil can significantly increase crop yield [21,26–28,43,52]. Finally, W application can improve crop yield and its constituent factors [53], especially in saline-alkali soil [29]. These results are consistent with our findings. Specifically, we found that the effective panicle number, number of total filled grains, 1000-grain weight, and seed setting rate of rice significantly increased after applying a modifier (P, F, and W), leading to improved rice yield.

Based on these findings, we conclude that P, F, and W interact with each other. Still, the combination of F and W and P and W or F differently affect yield, in the following order: F and W > P and W > P and F. Previous studies have shown that P combined with F can significantly improve crop yield [54] and maintain soil moisture in salt-affected soils [55], which is consistent with our finding. Specifically, we found that the interaction of P with F can improve soil conditions and crop yield. In this experiment, based on a triple regression equation, we concluded that applying P, F, and W positively impacted rice yield, and that P had the greatest effect on yield. Overall, the soda saline-alkali soil is characterized by high pH and contains soluble salts [56], thus becoming the main factor for rice yield reduction. However, P was replaced with a Ca^{2+}–Na^{+} ion, improving the chemical properties of the soil [57,58].

The main aim of this study was to determine the optimal application of fertilizer in a saline-alkaline environment [59]. Regarding our primary aim, choosing the right model to address the aim is important. The "3414" design to evaluate optimal modern fertilizer rate is a secondary regression model with the advantages of reducing the number of treatments to be applied and improving efficiency; however, its pseudo-synthetic power is low [60]. The ternary quadratic regression model would be ideal in practice. In this study, the application amounts of P, F, and W were considered independent variables, and rice yield was the dependent variable to establish the ternary quadratic regression equation. After the significance test ($p < 0.01$), the resultant coefficient of the quadratic term was negative, while the coefficient of the primary term was positive. These findings align with the law of decreasing fertilizer returns, and the equation fitting was successful. As the ternary function is a set of points in four-dimensional space, it cannot be calculated using a method similar to that used to solve binary equations. Additionally, even the only stable point cannot be asserted to be the optimal solution [61,62]. Therefore, the frequency analysis method was used to optimize the analysis. The results showed that the optimal application combination of P, F, and W was as follows: P, 29.09–32.38 $t \cdot ha^{-1}$; F, 40.36–46.97 $t \cdot ha^{-1}$; and W, 19.57–23.95 $t \cdot ha^{-1}$. Additionally, a significant reduction in soil pH was observed, which may improve soil salinity.

After rice is planted in saline-alkali soil, the salt content is reduced through capillary movement of the root layer and evaporation from the soil surface, and organic matter is produced due to underground root decay, increasing the partial pressure of carbon dioxide in soil [63–65]. Previous studies have shown that applying Ca^{2+}-rich P mainly replaces Na^{+} in the soil, thus removing Na^{+} and reducing Na^{+} absorption by plants. At the same time, the acidity of P neutralizes alkaline soil to a certain extent, and by replacing Na^{+} with more Ca^{2+}, the stability of soil aggregates can improve, which is conducive to plant growth; however, whether this approach has antagonistic effects on other soil nutrients needs to be further studied [57,58,66,67]. This strategy improves soil structure, increasing water conductivity. Overall, the toxic effect of the saline-alkali soil on rice is greatly reduced [67,68]. Other studies have shown that after applying F, the soil absorbs more Ca^{2+}, Mg^{2+}, and K^{+}, resulting in a decrease in the soil ESP, which reduces soil alkalinity [69]. W is rich in humic acid, which can regulate soil pH to a certain extent [70,71]. These results indicate that there may be a synergistic mechanism between P, F, and C. Additionally, the results of this study show that the combined application of P, F, and C can significantly improve rice yield. We found that the pH and EC of the soil in the root zone in the 14 treatments were largely similar across the four soil layers, indicating that the amendments had a slight effect on the root layer of the soil. This result is consistent with that of a previous study [66]. In that experiment, the pH of soil treated with $P_3F_2W_2$ was the lowest, while EC was the highest, followed by soil treated with $P_2F_2W_2$. This may be because, compared with the $P_2F_2W_2$ treatment, an increased amount of P is required for

$P_3F_2W_2$, leading to more Ca^{2+} replacing Na^+ at the soil binding site, thus reducing Na^+ and soil pH. In our experiment, due to the application of P and F, the salt content increased in topsoil, and soil EC became slightly higher than that in the control treatment. In the future, salt content should be reduced by increasing leaching times.

5. Conclusions

We found that rice yields on cultivated saline-sodic land can be increased through the application of different combinations of P, F, and W. Our comprehensive analysis showed that the optimal combination was as follows: P, 29.09–32.38 $t \cdot ha^{-1}$; F, 40.36–46.97 $t \cdot ha^{-1}$, and W, 19.57–23.95 $t \cdot ha^{-1}$. Thus, the $P_2F_2W_2$ treatment represents an optimal combination of amendments. Overall, this study provides a robust theoretical and technical basis for the worldwide improvement of severe saline-sodic land.

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